DETC2005-85283

Sherpa Moving Mass Entry Descent Landing System

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Abstract

We describe Sherpa – a Strap-on High-altitude Entry Reconnaissance & Precision Aeromaneuver system that utilizes a moving mass system within an entry capsule to land a spacecraft precisely onto the surface of Mars. Sherpa uses two sets of "strap-on" assemblies, one for high-altitude sensing using a terrain imager, and another for agile hypersonic flight using a moving-mass steering device. In this paper we focus on the moving mass system – a steering device that provides an agile trajectory control capability that is mechanically simple, completely internal to the vehicle, has high control authority, and is robust to mechanism failure. The Sherpa system takes a small fraction (5-10%) of the total system mass, and is capable of delivering payloads to within the proximity (~5 km) of a wide variety of landing sites including those at high-altitude (2.5+ km above the reference geoid).

1.0   INTRODUCTION

Sherpa is motivated by the fact that on Mars ballistic unguided landers typically have landing error ellipses that are 80+ km in extent. Targeted investigation of regions of small geographic extent (e.g. 10 km) is not possible with such a large landing ellipse, which also forces

the spacecraft to accommodate the wide variety of landing hazards that are more likely to be present in a larger area. This leads to increased spacecraft development costs and risks. Furthermore, landers with ballistic entry have no trajectory lift capability, and are therefore unable to land at high-altitudes (i.e. greater than 0-1 km above the reference geoid) in all Mars seasons with adequate margins for parachute deployment. This precludes their use over large portions of the planet including scientifically interesting regions in the southern highlands. Figure 1 shows the Mars terrain access made possible by a Sherpa type system. The Sherpa capabilities of precision landing and high-altitude access combine to increase the landing site choices from the few dozen for ballistic entry vehicles, to thousands of sites over a variety of latitudes and seasons. This supports many science objectives requiring targeted delivery of rover and subsurface payloads in support of the search for life and water, "ground-truth" verification of orbital-acquired data, and delivering of specialized payloads to sites of geologic interest.

As depicted in Figure 2, the Sherpa system's key actuation element is a "strap-on, actuator element consists of a **Variable Center-of-Mass** device utilizing two **Moving Ballast** masses within an annular ring mounted in the spacecraft capsule. The moving-mass actuator conforms to the perimeter of the entry vehicle and minimally impact accommodation of other payload elements. The ballast masses contain their own internal low-mass drive systems that allow them to be positioned anywhere along the annular ring which they share. The center-of-mass offset induced by the ballast modifies the aerodynamic trim angle-of-attack for the vehicle (in the direction aligned with the offset) and consequently generates aerodynamic lift aligned with that direction. This lift-force is used to precisely control the vehicle to a goal location above the target, as well as to provide the capability to land at high-altitudes. The actuator is fully internal to the vehicle with no exposure to the aerodynamic and aerothermal environment outside the capsule.

The Sherpa concept is in contrast to a thruster-based bank-angle control of the lift-vector with a fixed lift force [1,2]. Sherpa heritage is from the fixed-ballast and entry aerodynamics of

the Mars Viking missions [3], and ground test demonstrations of related moving-mass systems [4,5]. Reports in the unclassified literature describe the ground demonstration of a Deconing Device at Sandia National Laboratories, and related discussion of re-entry vehicle control using moving ballast element [4]. Our effort is focused on a Mars-specific system design adaptation and configuration, hardware prototyping, and verification using simulation. Table 1 details some of the target Sherpa performance capabilities.

Table 1. Sherpa target performance.	
Performance Feature	*Sherpa Goal*
Delivery Error that can be overcome (flight-path angle)	~0.5 deg
Tolerance to initial knowledge errors (flight-path angle)	0.25 deg
Lift-To-Drag Control Authority	Variable 0.0-0.24+
Entry Actuation System Complexity	Low: Electric motor
Earth-based Nav. (beyond standard Range, Doppler and Very Long Baseline Interferometry)	Not required
On-Board Attitude/Position propagation	Medium Grade IMU for ~2 min.
Error ellipse (3σ) at parachute deploy	~5 km
Landing Altitude (above geoid)	2.5+ km
Actuator Mass Percentage (ballast, thrusters, motors)	5-10%

2.0   DESIGN DRIVERS

Sufficient control authority is possible using traditional, high-heritage blunt-body aerodynamic shapes. Control actuations by lift-to-drag modulation is implemented by a moving ballast system whose elements are completely internal to the entry vehicle and protected from the harsh environment. Electro-mechanical elements and duty-cycles are tailored to the EDL descent profile to allow a low-mass implementation. A dual ballast system provides fail-safe operations and accommodates vehicle rotations and angle-of-attack constraints during different regimes of

the flight. The Sherpa actuator concept design is driven by several observations regarding EDL for a blunt-body, axi-symmetric vehicle entering into the Mars atmosphere at typical entry velocities, flight-path angles, and on-board state knowledge.

- The entire EDL interval is only of a few minutes duration. ***This enables mechanisms and sensors to be tailored for short-duration operation.*** Specifically, inertial propagation using a low-cost IMU sensor is feasible since gyro drift will be insignificant over these time scales. Actuator elements need to be designed for duty cycles lasting for only a few minutes.

- Between ~50 to ~150 seconds after entry, the vehicle experience significant dynamic pressure that is used to both slow the vehicle (by drag forces) but can also provide range control authority for the vehicle (using aerodynamic lift to steer the vehicle).

- Control authority to steer the entry capsule can be most efficiently provided by some form of aerodynamic lift-force modulation. For the class of blunt-body vehicles similar to the Viking entry capsule, control authority (expressed as Lift-to-Drag or L/D ratios) of 0.15-0.3 is aerodynamically achievable by varying the angle-of-attack. This in turn is most easily accomplished by offsetting the system center-of-mass by using ballast. Typical ballast system masses to achieve the range of lift-to-drag ratios is from 3-5% of the system mass for ballast located at 1/3 to 1/2 a vehicle radius away from the central axis-of-symmetry e.g. a 10 kg mass for a 300 kg entry vehicle. The cumulative range control authority of a vehicle with a nominal L/D ratio of 0.18 is ~150 km. This provides significant range control capabilities to not only overcome initial delivery errors (~40 km for a 0.5 degree flight-path-error) but also combat the results of atmospheric disturbances and un-modeled effects during the descent. The altitude gain using the lift capability of this vehicle over a ballistic vehicle is ~5km. ***This implies that a vehicle with a conventional Viking heritage aeroshape and high control authority (e.g. 0.18-0.24 L/D) has adequate performance for achieving both precision landing and high-altitude terrain access.***

- The control action at any given time affects the down-range distance achieved by the vehicle. For a vehicle with a 0.18 L/D ratio, range changes of up to ~2 km is achieved with the exercise of a 1-second duration lift control action near the peak dynamic pressure point in the trajectory. The final down-range position of the vehicle is a consequence of the cumulative effect of a number of control actions spanning the ~100 second interval of control-authority availability. This cumulative nature of the control action lends itself to consideration of on-board guidance designed to predict the error and take the control actions necessary to overcome the error. This is similar to the thruster-based, bank-angle controllers for precision EDL guidance [1]. The nature of the corrections is generally small once the large errors have been corrected. ***This enables the ballast mass actuators to be designed so as to exploit quiescent intervals to accumulate mechanical energy until a large control actuation is required.***

- Using two ballast masses provides a fully variable center-of-mass offset capability. ***This enables a vehicle to tune the lift authority to a high value (e.g. when peak dynamic pressure is available) and reduce it to a low value (e.g. when ready to deploy a parachute at a safe low trim-angle). It also allows the vehicle to independently modulate down-range and cross-range control authority.*** This latter capability also avoids the problem associated with bank-angle reversal used by conventional entry guidance schemes using a fixed ballast, where down-range control authority is lost during the intervals when the vehicle compensates for accumulated and induced cross-range errors [1].

- The ballast system is capable of achieving a trim angle of zero (by separating the ballast masses by 180 degrees) by actuating only one ballast elements. ***This enables system safing in the presence of a single ballast element failure. It also enables exo-atmospheric flight to be done with a symmetric and more stable mass/inertia configuration until stabilizing aerodynamic forces build up. Furthermore, this capability allows the vehicle to safely deploy parachutes at low angles-of-attack, thereby staying within the parachute qualification criteria for a number of previously validated Mars entry vehicle parachute systems.***

- The required ballast mass is comparable to the mass of the system elements required to implement the Sherpa system. ***This enables the ballast to be internally configured as useful mass with motors, batteries, gears, electronics, etc., replacing what would otherwise be "dead mass".***

- The use of internal moving masses to provide actuation protects the actuator from exposure to the harsh EDL aero-thermal environment. ***This enables a low-risk system when compared to propulsive attitude control systems [2] used to modulate bank-angle control and change the lift-vector.***

- A fully internal actuator preserves the integrity of the aero-shell with no external aerodynamic tabs, thruster nozzles, etc., that would be found on other actuator concepts [6]. ***This enables the use of high-heritage, fully validated, blunt-body, axi-symmetric aero-shapes that have previously flown to Mars (e.g. Viking, Pathfinder, MER) and which will be flown on the proposed MSL mission.***

- The ballast actuators can be counter-spun about the actuator ring axis in a direction opposite to the vehicle roll so that the center-of-mass offsets are in an inertially aligned de-spun direction. ***This enables the exploration of moderate spin-stabilization of the entry vehicle without significantly compromising the actuation capability.***

In the subsequent discussion, we refer to typical entry and descent profiles for a representative blunt-body vehicle with (modulated) lift control, lift-to-drag L/D ratio of 0.18, and ballistic coefficient 60 kg/m^2. We assume the vehicle is flying with its lift-vector "sideways" (i.e. it is not utilizing its lift for lofting the vehicle trajectory or for range control) and serves as reference to examine the effects of control actions.

3.0 PRECISION AEROMANEUVER MOVING MASS SYSTEM

Our moving-mass ballast is configured so that the actuator ring is located as far forward to the nose of the vehicle as possible to provide a favorable axial center-of-mass location for maximal

aerodynamics stability without occupying crucial volume needed for most payloads. When the ballast masses within the actuator are 180 degrees apart, the actuator provides a zero radial center-of-mass offset. When they are close to each other, the ballast masses provide the maximum radial center-of-mass offset, with the offset direction a function of the angular position of the ballast masses within the ring. Intermediate positions of the ballast masses gives a variable center-of-mass offset – both in terms of the magnitude as well as the direction.   The presence of two ballast masses also provides a measure of redundancy and fault-protection.

The vehicle, as a result of the center-of-mass offset, trims at a negative angle-of-attack to generate lift (unlike an aircraft, blunt-bodies generate lift for negative angles-of-attack because of the predominance of the axial force over the lateral force). The magnitude of the radial center-of-mass offset determines the magnitude of the trim angle-of-attack and hence the L/D ratio. Figure 3 is a plot of vehicle control-authority and depicts how the vehicle can affect its down-range distance at any instant it chooses to exercise its maximum available lift-based control action. The angular location of the ballasts controls the direction in which the vehicle trims, and hence the lift vector direction. If the entry vehicle were rotating about its axis of entry (to provide enhanced inertial stability during entry), then the two ballast masses would counter-rotate about the vehicle axis to "de-spin" the lift vector and allow it to be controlled in an inertially referenced direction. Such ballast angular motions also compensate for roll motions induced by inevitable changes to heat-shield geometry during flight and other inertial moment disturbance effects.

The aerodynamic aspect of the system is illustrated in Figure 4. For simplicity only one of the ballast masses is shown, both before and after a representative control action (in this example, a 180 degree displacement). We depict dynamics related quantities of interest including the freestream velocity, the angle-of-attack between the vehicle and the freestream velocity, and the net force felt by the body at a nominal center-of-pressure. An iso-potential line perpendicular to the force vector and through the ballast gives an indication of a level surface above which

control effort is required to "climb up". A dark green circle indicates the center-of-mass of the lander system.

3.1   Ballast Actuation

The Sherpa Ballast Mass concept is notionally shown in Figure 5. A small low-power electric motor with a gear-box (henceforth referred to as just the motor) is internal to the ballast system and provides the primary mechanical motive force. The electric motor is potentially connected to a small internal flywheel that allows the storage of mechanical energy used to make fast motions. Alternatively, the motor can be sized to provide large transient torques. A reversing clutch-brake device connects these internal rotating elements to the exterior wheel-shape of the ballast system, allowing the ballast to roll along its axis in either direction. A rack-and-pinion interface between the ballast wheel and bottom surface of the annular ring of the actuator provides for deterministic rolling and braking operation of the wheel. The rest of the ballast wheel contains additional ballast mass (e.g. machined tungsten), batteries, electronics and communication elements to bring the overall mass of the ballast system to the value required to offset the center-of-mass. Communication between the ballast element and other capsule elements could be by wireless means, the technology for which is rapidly maturing for space-flight applications [7].

The salient feature of the actuator is that the ballast mass motions are constrained to lie on the flat lower surface of the annular ring, which is inclined at a small angle to the force vector being experienced by the vehicle. Angular motion of the ballast almost always requires doing mechanical work to lift the ballast against the acceleration vector. On-board guidance will command the speed and direction of the rolling ballast. The final location achievable by the ballast is a function of the initial internal flywheel (if present) spin-up, available motor torque, braking torque/actions, and the induced capsule-body attitude reconfiguration. After completion of an initial fast responsive ballast motion, a slow-speed ballast wheel roll actuation can be initiated to roll the ballast even further or refine the ballast location.

Our moving-mass actuator compares favorably to alternative approaches to generating and controlling aerodynamic lift. One such technique is to generate the lift-vector by means of an aerodynamic asymmetry (e.g. a tab on one side of the capsule), or by a fixed ballast to offset the capsule center-of-mass. This still requires that the direction of lift-vector be controlled by other means to allow down- and cross-range trajectory control. One standard technique adopted for a variety of entry vehicles is to change the bank angle of the vehicle (so as to rotate the lift vector which is fixed with respect to the vehicle in these cases) through a range of angles [2]. Such bank-angle control necessitates either a thruster-based attitude control system or modulation of an aerodynamic surface (e.g. a movable fin/tab) to generate a roll moment. The former method requires the full complexity of a propulsion system with its fuel and pressurization tanks, thrusters, valves and vehicle exterior penetrations. The latter requires the design of mechanisms and a controller that can operate in the severe aerodynamic and aerothermal regime encountered by the capsule during hypersonic flight. Both techniques also do not have fail-safe attributes – the misfiring of a thruster or a stuck aero-control surface leads to uncontrollable vehicle roll and the potential for large instabilities. In contrast, the Sherpa actuator can easily safe the vehicle in the event of a single ballast mass failure by moving the other ballast mass to achieve a neutral, zero center-of-mass offset system. At that point, the vehicle behaves as a ballistic vehicle i.e. safe EDL but without a precision landing capability.

3.2   Guidance and Control Issues

From a guidance viewpoint, the actuator provides a continuous lift-vector reorientation control similar to that achieved by a bank-angle vehicle controller used for a fixed-ballast or aero-tab equipped lifting body. However, the Sherpa actuator also has the ability to simultaneously control both down- and cross-range, and modulate the magnitude of the angle-of-attack. Note that no bank-reversal maneuvers are required with Sherpa since lift-modulation can be applied to the cross-range direction by simply rotating the ballast elements to a new angular position. This avoids the adverse reversal events needed in traditional bank-angle control schemes where down-range control-authority is temporarily lost during the reversal maneuver.

Our design of the on-board guidance builds upon calculus-of-variation methods used in optimal control for bank-angle landing system guidance [1] and the dynamics of under-actuated multibody systems [8]. The guided-entry problem into the Martian atmosphere has some unique attributes that can be exploited to simplify the variable center-of-mass actuation and control problem and system design. The initial control action would be to null any navigation/delivery errors, with subsequent control actions combating deviations from the predicted target point. Experience with traditional thruster-based bank-angle modulation schemes on vehicles with a 0.18 L/D control authority indicate that overall lift-vector reorientation seldom exceeds 360 degrees of total angular travel over the entire control activity duration of only 2-3 minutes. Adequate system response is achieved with small angular accelerations (10 deg/s^2) to modulate the lift-vector [1]. Furthermore such changes in angle are typically needed for only short periods within the overall control activity, while there are long periods where no bank-angle change is required. These observations lead to the expectation that our moving mass controller will require only a limited number of actuation events over a short time scale. With sufficient L/D authority (e.g. L/D of 0.24+, consistent with Viking heritage) these control actions can even wait for some errors to accumulate before performing a ballast relocation maneuver for a specified duration. This implies that the actuator drive mechanisms need not be sized for continuous, high-speed motions but can be designed to meet the needs of a more intermittent high-torque duty cycle, resulting in mass and power savings.

3.3   Vehicle Stability

Models of the aerodynamic system interactions with the ballast system are derived from a combination of nonlinear analytic multi-body models and quasi-analytic aerodynamic coefficient expressions valid over large ranges of Mach numbers using cross-flow velocity terms [9]. Spectral analysis of the models and Liapunov methods give indications of stability and stability margins. The large-scale stability (excluding small limit-cycle behavior) for the vehicle is inherent in the passive hypersonic aerodynamics of blunt-body entry vehicles. Traditionally, additional stability for entry vehicles has been provided by spin-up of the entire vehicle (e.g. a 2

rpm spin value for the Pathfinder vehicle provided for both stability and disturbance motion averaging), or by rate-damping on thruster-based attitude control systems. Additional stability for a vehicle with a Sherpa actuator can be provided by means of a small spin of the entry vehicle about the axis of symmetry. This does not affect the lift control capability because it can be compensated for by the "de-spin" roll capability of the ballast mass actuator. Active vehicle stability augmentation is also achieved by dynamically adjusting the vehicle center-of-mass using the ballast system.

3.4   Concept Verification.

We have minimized the number of challenges facing the validation of the Sherpa precision landing concept by adopting a conservative approach to entry aerodynamics and using extrapolations of well-understood sensing and navigation technologies. Nevertheless, a key challenge will be to carefully understand the interactions between different components of the system. The range of delivery accuracies for a typical Mars mission together with the precision of the Sherpa high-altitude navigation determines the control authority that must be provided in terms of the lift-to-drag ratio. The disturbances during descent, and the uncertainties in system, environmental and navigated parameters determine the angular range and responsiveness of the center-of-mass actuator. The stability margins need to be analyzed, and possibly augmented by suitable vehicle spin-up and actuator control. The system has to work over a variety of dispersed cases and therefore needs to be robust to these changes. Careful trade-offs need to be made to ensure that this robustness is not achieved at a high cost in system mass – which would make the strap-on concept unattractive to potential users.

Accurate modeling and high-fidelity simulation of EDL dynamics is key to both analysis as well as verification of the research results. We use high-fidelity aerodynamic and multi-body dynamics modeling and simulation tools to address these system design and validation challenges. The DSENDS (Dynamics Simulator for Entry, Descent and Surface landing) tool [10,11,12] provides full multi-body and flex-body dynamics modeling, the MarsGram

atmosphere model, table-driven aero-coefficient models, synthetic and enhanced terrain models, image sensor simulations, and a full repertoire of spacecraft sensor and actuator device models [13]. The DSENDS simulator is an EDL-specific deployment of the Darts/Dshell dynamics and spacecraft simulator that has been used in flight-critical applications such as Cassini, Mars Pathfinder, etc. DSENDS also provides facilities to develop as well as interface (e.g. through Matlab® and Simulink®) navigation, guidance and control modules. The DSENDS simulation is also used to generate influence functions used in guidance development. The Dsends simulation framework includes the Darts (Dynamics algorithms for real-time simulation) real-time, flexible-body, multibody dynamics package and the Dshell (Darts shell) tool for integrating reusable hardware and environmental models with Darts to develop high-fidelity spacecraft engineering simulations. The Dshell-based simulations can be used as stand-alone simulations, or embedded within Matlab/Simulink design environments. They can also be run in closed-loop with flight software, and within real-time hardware-in-the-loop testbeds. Several NASA missions including Cassini, Mars Pathfinder, Deep Space 1, SIM and Starlight, have used Dshell simulations for their real-time and non-realtime testbed simulation needs. The Mars Science Laboratory (MSL) mission in 2009 is planning on using DSENDS as one of its mission/system simulation tools. In addition to providing the infrastructure for developing reusable model libraries, the Dshell framework provides a host of simulation infrastructure services such as data logging, check-pointing, simulation data peek/poke capability, graphical data monitoring, and 3D graphics visualization. The Dshell architecture is modular and supports easy configuration of complex simulations at run-time. The Dshell simulation software currently runs on Unix (Solaris, Irix, Linux) and the VxWorks real-time platforms.

4.0   CONCLUSIONS AND FUTURE WORK

We have described the features of a moving-mass actuator for entry control and guidance for Mars landers. This concept has the potential to be a low-cost means of achieving a precision landing capability for future Mars missions. Further analysis is underway to be followed by a terrestrial test program. The Sherpa actuator will be prototyped to demonstrate feasibility and test

performance. This prototype will be built with commercial off-the-shelf (COTS) parts, but within flight-system constraints and issues that would influence the design. The prototype will be tested by affixing the actuator to a 2-axis tilt platform programmed to execute a series of attitude motions representative of entry attitude dynamics. We are also investigating the feasibility of performing a number of low altitude drop tests.

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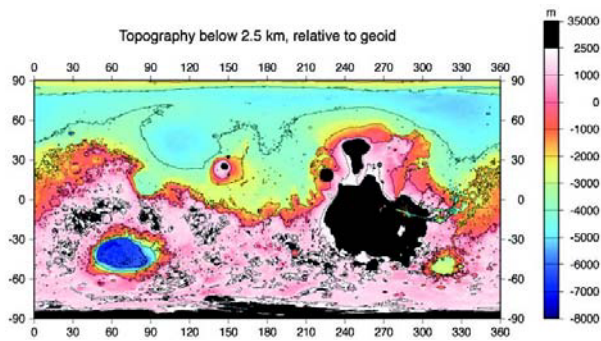
Figure 1. Map with 2.5+ km regions in black shows that large areas on Mars are accessible to Sherpa equipped landers.
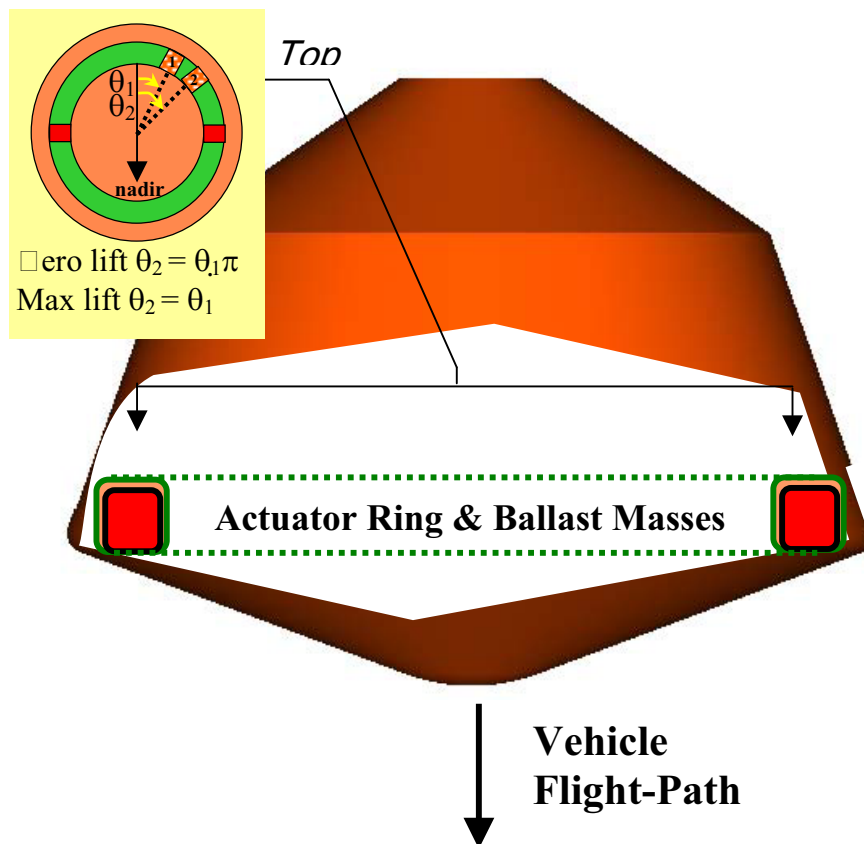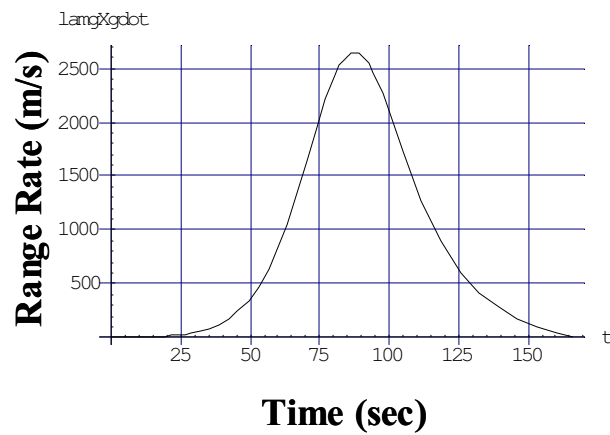

Figure 2. Sherpa Actuators

Figure 3. Control Authority profile shows change in range distance per duration of control action at different points along the EDL timeline
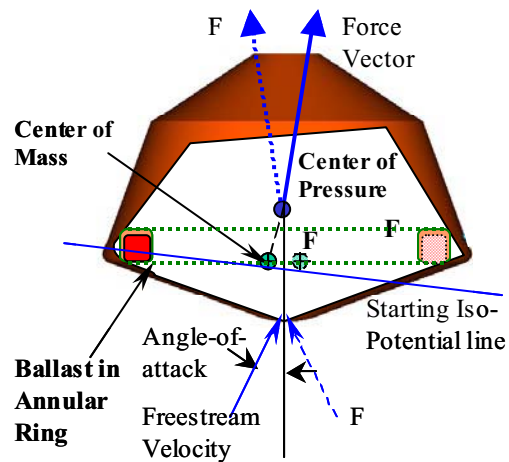

Figure 4. Actuator Configuration Concept. The solid lines in this figure represent the initial location of all of the elements. Dotted lines with a label `F` represent the final location of the elements Actuated elements are indicated in red and passive elements are indicated in green.
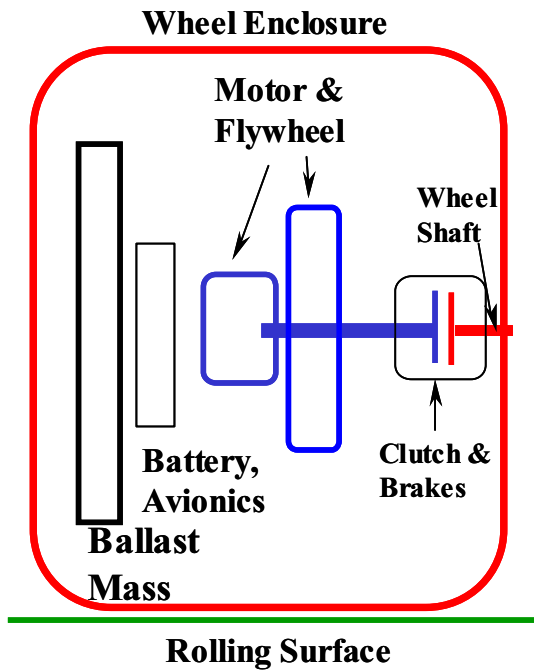
Figure 5. Ballast Configuration Concept (notional) allows utilization of the internal mass to provide moving-mass actuation capability.